# The effect of unilateral hand contractions on psychophysiological activity during motor performance

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## Abstract

**Objectives:** Conscious engagement in movement control can influence motor performance. In most cases, the left hemisphere of the brain plays an important role in verbal-analytical processing and reasoning, so changes in the balance of hemispheric activation may influence conscious engagement in movement. Evidence suggests that unilateral hand contractions influence hemispheric activation, but no study has investigated whether there is an associated effect of hand contractions on verbal-analytical processing and psychophysiological activity during motor performance. This study was designed to examine whether pre-performance unilateral hand contraction protocols change verbal-analytical involvement and psychophysiological activity during motor performance. **Design**: A repeated measures crossover design was employed. **Methods**: Twenty-eight participants completed three hand contraction protocols in a randomised order: left, right and no-hand contractions. Electroencephalography (EEG) measures of hemispheric asymmetry were computed during hand contractions. A golf putting task was conducted after each protocol. EEG connectivity between sites overlying the left verbal-analytical temporal region (T7) and the motor planning region (Fz) was computed for the 3-sec prior to movement initiation. Additionally, electrocardiography (ECG) and electromyography (EMG) signals were analysed 6-sec prior to movement initiation until 6-sec after. Golf putting performance was obtained by distance from the target and putter swing kinematics. **Results**: Contralateral hemisphere activity was revealed for the left and right-hand contraction conditions. During motor planning, the left-hand contraction protocol led to significantly lower T7-Fz connectivity, and the right-hand contraction protocol led to significantly higher T7-Fz connectivity than the other conditions. EMG, ECG and kinematic measures did not differ as a function of condition. Importantly, T7-Fz connectivity mediated the relationship between hand squeezing and motor performance (distance from the target). **Conclusion**: The EEG results suggest that pre-performance unilateral hand contractions influence the extent of verbal-analytical engagement in motor planning, which in turn influences motor performance. However, the hand contractions did not influence cardiac activity, muscle activity or kinematics.

*Key words: hand contraction protocol; hemisphere-specific priming; EEG; heart rate; movement kinematics*

## Introduction

A link between conscious processes and motor performance is found in studies using electroencephalography (EEG) to examine communication (synchronization) between different regions of the brain (Babiloni et al., 2011; Deeny, Hillman, Janelle, & Hatfield, 2003; Gallicchio, Cooke, & Ring, 2016; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011). Evidence from these studies suggests that high conscious engagement in motor performance is associated with more synchronous neuronal activity, indexing greater functional communication between the left temporal T7 region of the brain (involved in verbal-analytical processing), and the frontal midline Fz region of the brain (involved in motor planning) (Babiloni et al., 2011; Deeny et al., 2003; Gallicchio et al., 2016; Zhu et al., 2011).

Compelling evidence for the link between conscious control of movements and verbal-analytical processes has been reported by Zhu et al. (2011, Experiment 1). They measured propensity to consciously control motor skills using the Movement Specific Reinvestment Scale (MSRS, Masters, Eves, & Maxwell, 2005). Participants with a lower propensity to consciously control movements displayed lower T7-Fz communication (e.g., coherence) than participants with a higher propensity for conscious control, during the 4-sec preceding golf putts (Zhu et al., 2011). Co-activation between the left temporal and frontal regions is also associated with motor performance. For example, Gallicchio et al. (2016) reported that T7-Fz connectivity was lower in the final seconds preceding successful golf putts compared to unsuccessful golf putts, suggesting that reduced or suppressed verbal-analytical processing is a feature of effective motor performance. In sum, reduced left temporal-frontal synchronicity may be associated with less verbal, more procedural, processing of movements.

Attempts to reduce verbal-analytical engagement during motor performance have used neuro-stimulation to suppress activity in the left hemisphere (Landers et al., 1991;

Snyder et al., 2003; Zhu et al., 2015). For instance, Zhu et al. (2015) found that cathodal (i.e., inhibitory) transcranial Direct Current Stimulation (tDCS) over the left dorsolateral prefrontal cortex promoted lower verbal-analytical engagement when practicing a golf putting task, compared to sham stimulation (i.e., placebo). However, tDCS is not a practical or accessible training method for the majority of performers, and ethical concerns about such extreme training methods have been raised (Davis, 2013).

Using a slightly less shocking method, Beckmann, Gröpel, and Ehrlenspiel (2013) and Gröpel and Beckmann (2017) asked semi-professional athletes (gymnastics, soccer, badminton and taekwondo) to squeeze a stress ball in either the left hand or the right hand for 45-sec before performing under competitive pressure. They reasoned that due to the contralateral coupling between our hands and our brain (i.e., the brain area controlling the right hand resides in left hemisphere, and vice-versa), squeezing the right hand should prime the left (verbal-analytic) hemisphere and squeezing the left hand should prime the right (visual-spatial) hemisphere. Results showed that left-hand contractions resulted in more stable performance under pressure than right-hand contractions. The authors argued that left-hand contractions prevented breakdown under pressure by activating the right hemisphere and deactivating the left hemisphere, which reduced disruptive verbal-analytical control of the movements (Beckmann et al., 2013; Gröpel & Beckmann, 2017). Beckmann et al. (2013, Experiment 3) additionally found that right-hand contractions magnified the effect of pressure, with participants performing worse when they carried out right-hand contractions prior to performing. They suggested that since right-hand contractions activated the left hemisphere, they potentially increased the likelihood that pressure would cause disruptive verbal-analytical involvement in performance. However, it is important to note that this interpretation cannot be confirmed since Beckmann and colleagues did not directly measure cortical activity in their studies.

Studies that did record cortical activity during unilateral hand contractions have revealed inconsistent results. For example, some studies revealed that unilateral hand contractions result in lower alpha power (i.e., increased brain activity) in the contralateral hemisphere (Gable, Poole, & Cook, 2013; Harmon-Jones, 2006; Peterson, Shackman, & Harmon-Jones, 2008; Schiff, Guirguis, Kenwood, & Herman, 1998). However, Cross-Villasana, Gropel, Doppelmayr, and Beckmann (2015) revealed that unilateral hand contractions produced lower alpha power over both hemispheres. Furthermore, they revealed that immediately after left-hand contractions ceased, whole scalp alpha power increased, indicating widespread deactivation (Cross-Villasana et al., 2015). This latter finding challenges Beckmann and colleagues suggestion that left-hand contractions are beneficial because they activate the right hemisphere. However, it does support the argument that left-hand contractions can deactivate the left hemisphere, perhaps suppressing verbal-analytical engagement in motor planning. Taken together, these findings indicate that hemispheric activity can be altered by hand contraction protocols. However, their effects on verbal-analytical processes have yet to be established. Specifically, no study has examined the effect of unilateral hand contractions on T7-Fz connectivity during the final moments of motor preparation. These final moments are important for establishing the level of conscious monitoring and control of the movement (e.g., Deeny et al., 2003; Gallicchio et al., 2016; Zhu et al., 2011). Therefore, measurement of cortical activity, especially T7-Fz connectivity, is required to more rigorously examine the proposed relations between left-hand contractions, verbal-analytical engagement and motor performance.

Finally, no studies have investigated the effects of hand contraction protocols on physiological and kinematic measures that may also relate to verbal-analytical engagement and motor performance outcomes (Cooke, Kavussanu, McIntyre, & Ring, 2010). Although Cooke et al. (2014) did not examine hand contractions, they did report greater heart rate deceleration during the 6-sec preceding motor performance in skilled versus low skilled golfers. Therefore, heart rate deceleration could offer another corroborative physiological measure that is sensitive to the amount of verbal-analytical engagement during motor planning (Cooke et al., 2014; Neumann & Thomas, 2009; Neumann & Thomas, 2011; Radlo, Steinberg, Singer, Barba, & Melnikov, 2002). Similarly, more automatic motor control is also associated with lower muscle activity (Lohse, Sherwood, & Healy, 2010; Vance, Wulf, Tollner, McNevin, & Mercer, 2004; Zachry, Wulf, Mercer, & Bezodis, 2005). For example, Lohse et al. (2010) revealed lower muscle activity when participants adopted an external focus of attention while throwing darts, compared to when they consciously monitored their technique. Finally, movement kinematics can also be linked to verbal-analytical engagement in motor planning (Cooke et al., 2014; Malhotra, Poolton, Wilson, Omuro, & Masters, 2015; Masters, Poolton, Maxwell, & Raab, 2008; Maxwell, Masters, & Eves, 2003). For example, Maxwell et al. (2003) revealed that verbal-analytic engagement in motor planning was associated with a less fluid technique. The assessment of such measures alongside T7-Fz connectivity may therefore provide new insight into the mechanisms underpinning the effects of unilateral hand contraction protocols on performance.

The present study is the first to investigate the effect of unilateral hand contraction protocols on psychophysiological and behavioural markers of golf putting performance. The aim was to gain a better understanding of whether pre-performance unilateral hand contractions have an effect on verbal-analytical processes involved in motor performance. Three hand contraction protocols (left, right and no-hand) were performed in a repeated measures crossover design, before performance of a golf putting task. Measures of alpha power (8-12 Hz) between homologous electrode pairs were first computed during the hand contraction protocols to verify that left-hand contractions activated the right hemisphere, and that right-hand contractions activated the left hemisphere. Cortical activity was then examined further by measuring the high-alpha power (10-12 Hz) connectivity level between the verbal-analytical left temporal (T7) region and the motor planning (Fz) region during preparation for each golf putt. Cardiac activity (electrocardiography), muscle activity (electromyography), kinematics, and golf performance were tested as supporting measures of verbal-analytical engagement in motor planning. Mediation analyses were employed to examine whether our EEG and psychophysiological indices of verbal-analytic engagement are the mechanisms underpinning any effect of hand contractions on performance.

Based on the behavioural findings of Beckmann et al. (2013) and Gröpel and Beckmann (2017), we predicted that unilateral hand contractions would influence verbal-analytical involvement (i.e., inferred by changes in T7-Fz connectivity) during movement planning. Specifically, we predicted that the left-hand contractions would lower verbal-analytical involvement during motor planning compared to right-hand and no-hand contractions, and that right-hand contractions would raise verbal-analytical involvement in motor planning compared to left-hand and no-hand contractions. Consequently, lower verbal-analytical engagement during the left-hand contraction protocol was expected to promote greater heart rate deceleration, lower muscular activity, smoother kinematics when initiating the golf putt and better outcome performance compared to the right-hand and no-hand contraction protocols (Cooke et al., 2014; Lohse et al., 2010; Neumann & Thomas, 2009; Radlo et al., 2002; Zachry et al., 2005). The opposite effects were predicted for the right-hand contraction protocol. Finally, we predicted that the effects of hand contractions on T7-Fz connectivity and our ECG, EMG and kinematic measures would mediate the relationship between hand contraction protocols and performance.

## Methods

### Participants and design

Twenty-eight people were recruited to participate in the experiment. Three participants who had major artefacts in their EEG signal were excluded from further analysis, resulting in a final sample of twenty-five participants (mean age = 26.52, SD = 5.08, female = 15). To control for handedness, only right-handed participants were included (> 70, Edinburgh Handedness Inventory, Oldfield, 1971). All participants had normal/corrected vision. The participants were instructed not to consume alcohol or drugs 24-hours prior to testing or caffeine 3-hours prior to testing, and to obtain at least 6-hours of sleep the night before testing. A repeated measures crossover design was adopted, with participants performing three different protocols (right, left and no-hand contractions). The order of protocols was counterbalanced within participants. This study was approved by the University (Human) Research ethics committee.

### Task

The experiment consisted of a pre-performance hand contraction protocol followed by a golf putting task. The hand contraction protocol required participants to firmly contract a stress ball at a self-paced rate for 45-sec either with their left hand or right hand, or to place their hands on their lap and hold them still for 45-sec (no-hand contraction condition). The researcher instructed the participants to sit quietly and to not talk or make large movements during these protocols, in order to control for muscle activity artefacts.

After each protocol, participants performed 25 golf putts on an artificial grass surface, using a standard length (90-cm) golf putter and a regular-size (diameter 4.7-cm) golf ball. The target was a 1-cm diameter white sticker on the putting surface positioned 2.4-m from the initial starting point. Mean radial error (mean distance in any direction from the target) was assessed.

## Measures

### Psychophysiological measures.

EEG data was used to assess cortical activity during the pre-performance hand contraction protocols (e.g., Gable et al., 2013) and during preparation of the golf putts (e.g., Zhu et al., 2011). EEG was recorded from thirty-two (32) active electrodes positioned using the 10-20 system (Jaspers, 1958): Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, and O2. Additionally, active electrodes were positioned on each mastoid, at the outer canthus and below each eye to record vertical and horizontal electrooculogram (EOG). Monopolar recorded signals were sampled at 1024 Hz, without an online filter, using an ActiveTwo amplifier (Biosemi, The Netherlands).

During the pre-performance protocols, we were primarily interested in cortical asymmetry (i.e., right hemisphere minus left hemisphere) in the broad alpha band frequency (i.e., 8-12 Hz), as previous studies have demonstrated the effects of unilateral hand contractions on broad-band alpha (Cross-Villasana et al., 2015; Gable et al., 2013; Harmon-Jones, 2006; Peterson et al., 2008). During preparation of the golf putt, we were interested in connectivity in the high-alpha frequency band (i.e., 10-12 Hz), as this portion of the alpha frequency is thought to be specifically related to task specific attentional processes and cortico-communication (for a review see Klimesch, 1999; Smith, McEvoy, & Gevins, 1999).

Electrocardiography (ECG) was used during golf putting performance, to assess cardiac activity (Cooke et al., 2014; Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011). Silver/silver chloride spot electrodes (BlueSensor SP, Ambu, Cambridgeshire, UK) were placed on each clavicle and on the lowest left rib. The ECG signal was amplified (Bagnoli-4, Delsys, Boston, MA), filtered (1-100 Hz) and digitized at 2500 Hz with 16-bits resolution

(CED Power 1401, Cambridge Electronic Design, Cambridge, UK) using Spike2 software (version 5, Cambridge Electronic Design).

Electromyography (EMG) was used to obtain muscle activity during golf putting for the extensor carpi radialis and flexor carpi ulnaris muscles in the left arm (Cooke et al., 2014; Cooke et al., 2011). Differential surface electrodes (DE 2.1, Delsys) were placed on the belly of the muscles and a ground electrode (BleuSensor SP, Ambu, Cambridgeshire, UK) was placed on the left collarbone. The EMG signal was amplified (Bagnoli-4, Delsys), filtered (20-45 Hz), and digitized at 2500 Hz with 16-bit resolution (Power 1401) using Spike2 software.

**Golf putting performance measures.**

The golf putting performance was determined by the mean radial error (cm), representing the mean distance between the final position of the ball and the centre of the target. This measure was computed with *ScorePutting* software (written in National Instruments LabVIEW), which uses the photographs from a camera system directly placed above the targets to control for angle differences (Neumann & Thomas, 2008).

**Golf kinematics.**

A triaxial accelerometer (LIS3L06AL, ST Microelectronics, Geneva, Switzerland) and amplifier (frequency response of DC to 15 Hz) were attached to the rear of the putter head in order to measure movement kinematics (Cooke et al., 2014; Cooke et al., 2011). Acceleration of the golf putter from downswing until ball contact was calculated for the x, y and z-axes (representing the lateral, vertical and back-and-forth movement of the club head), to determine club head orientation, swing height and impact force (Spike2, version 5, Cambridge Electronic Design).

## Procedure

Participants were informed about the context of the study and signed an informed consent form prior to the start of the experimental procedure. The EEG, ECG and EMG equipment were set up and a 2-min EEG resting state measurement was performed (1-min open eyes and 1-min closed eyes).

Participants first completed 130 putts as part of a separate investigation of the psychophysiological corollaries of practice (data not reported here). The putts served to familiarise participants with the task. This was followed by performing one of the three pre-performance hand-contraction protocols (left, right or no-hand contractions) while seated. Immediately after each protocol, participants were instructed to stand-up and perform 25 self-paced golf putts, aiming for the target as accurately as possible. The time lag between the end of the squeezing protocol and the start of the putting task was approximately 10-sec. A photograph of the final position of the golf ball was taken after each trial. The researcher then collected the golf ball and positioned it for the next trial, thereby standardising the inter-trial interval, and reducing the need for participants to move in-between putts. This procedure was repeated for all conditions (three times in total) and took on average 5-min and 53-sec per condition.

## Analysis

### Pre-performance hand contraction protocols.

EEG signals captured during the hand contraction protocols were processed offline with EEGLAB software (Delorme & Makeig, 2004) running on MATLAB (Mathwork, Inc., USA version 2018b) to compute the power asymmetry. The signals were first resampled to 250 Hz, re-referenced to the average of all electrodes, and filtered (.01-30 Hz bandpass filter). The IAF toolbox was used to adjust the alpha frequency band for each participant based on their individual alpha frequency peak, determined from the baseline measure (Corcoran, Alday, Schlesewsky, & Bornkessel-Schlesewsky, 2018).

The signals were then subjected to a threshold-based artefact removal procedure, where any 250-ms window containing signal fluctuations exceeding ±150 μV was rejected (ERPLAB Toolbox, Lopez-Calderon & Luck, 2014). Independent Component Analyses were then performed via the RunICA infomax algorithm (Makeig, Bell, Jung, & Sejnowski, 1996) to identify and remove any remaining artefacts and non-neural activity (e.g., eye-blinks) from the signal. An average of 5.76 components were rejected. The clean signal was then subjected to a time frequency analysis, to obtain the estimate of instantaneous alpha power for the 38-sec of the hand contraction protocols. The total of 45-sec was reduced by 7-sec, due to some participants showing increased artefacts at the end. This analysis was performed by convolving the Fast-Fourier Transform (FFT) power spectrum of the signal with a family of complex Morlet wavelets and eventually taking the inverse FFT (Cohen, 2014). All power values were then log transformed to control for skewness and inter-individual differences. Finally, the transformed values were used to compute the asymmetry scores of the homologous electrode pairs close to the cortical regions involved in hand movements (e.g., Grefkes, Eickhoff, Nowak, Dafotakis, & Fink, 2008): T8-T7, P4-P3, P8-P7, F4-F3, F8-F7, C4-C3, FC2-FC1, FC6-FC5, CP2-CP1, CP6-CP5 (right – left). This is a common way of calculating alpha asymmetry to identify the effects of a state manipulation (e.g., unilateral hand contractions) on the relative activation of the right hemisphere versus left hemisphere of the brain (e.g., Harmon-Jones, 2006). A higher asymmetry score signifies more activity in the left hemisphere (inverse of alpha activity) compared to the right hemisphere (Harmon-Jones, 2006; Wolf et al., 2015).

**Golf putting task.**

An optical sensor and microphone were used to mark movement initiation and ball contact in the continuous data (Spike2 and Actiview software, Biosemi), in order to analyse the psychophysiological measures prior to and during the golf putts. The optical sensor (S51-PA-2-C10PK, Datasensor, Monte San Pietro, Italy) was used to identify swing-onset by detecting when the infrared beam was broken by movement of the putter head. The microphone (NT1, Rode, Silverwater, Australia) was linked to a mixing desk (Club 2000, Studiomaster, Leighton Buzzard, UK) to detect putter-to-ball contact.

Connectivity prior to movement initiation was computed offline by processing the EEG signals (EEGLAB software) computed during the golf putt preparation. The signals were cut into epochs of 5-sec (4-sec prior to and 1-sec after movement initiation). Thereafter, the signals were filtered and cleaned with the same methods as for the *hand contraction protocols*. The signals were then baseline corrected (-.2 to 0-sec, where 0 = movement initiation; Ring, Cooke, Kavussanu, McIntyre, & Masters, 2015) and time-frequency analysis was performed (see *hand contraction protocols*) to obtain the phase angles. These phase angles were then used to compute connectivity between the left temporal (T7) and frontal (Fz) regions for the 3-sec prior to movement initiation, by calculating inter-site phase clustering (ISPC, Cohen, 2014).[1] We calculated $ISPC_{time}$ measuring phase angle differences across the electrodes over time: [2]

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[1] Two different methods have been used to measure synchronization in the sport science literature. Earlier work (e.g., Deeny et al., 2003) measured magnitude squared *coherence;* however, more recent research has measured inter-site phase *connectivity* (ISPC). ISPC is based on phase information only, which makes it independent of fluctuations in absolute power (Gallicchio et al., 2016).

[2] Cohen (2014) suggests that the ISPC *time* measure is appropriate when having relatively long epochs, with 3-sec considered as long.

$$\mathrm{ISPC}_{xy}(f) = \left| n^{-1} \sum_{t=1}^{n} e^{i(\theta_x(tf)-\theta_y(tf))} \right|$$

*N* is the number of data points; *i* is the imaginary operator; $\theta_x$ and $\theta_y$ are the phase angles of the recorded signal at two different scalp locations; *t* is the time point and *f* is the frequency bin. The $e^{i(\theta_x(tf)-\theta_y(tf))}$ represents the complex vector with magnitude 1 and angle $\theta_x$ - $\theta_y$ ; $n^{-1} \sum_{t=1}^{n} (.)$ denotes averaging over time points, and $|.|$ is the module of the averaged vector (Cohen, 2014; Lachaux, Rodriguez, Martinerie, & Varela, 1999). ISPC is given as a value between 0 (no functional connection) and 1 (perfect functional connection). Finally, values were Z-transformed (inverse hyperbolic tangent) to ensure normal distribution (Gallicchio et al., 2016).

The EMG and ECG signals 6-sec prior to until 6-sec after movement initiation were analysed offline in epochs of 1-sec (Cooke et al., 2014; Moore, Vine, Cooke, Ring, & Wilson, 2012; Neumann & Thomas, 2011). Heart rate was corrected for artefacts and R-wave peaks were identified. The intervals between the successive R-waves peaks were calculated and instantaneous heart rate (beats per minute, BPM) was calculated as 6000/(R-R interval). Muscle activity was assessed by rectifying the EMG signal and averaging over 0.5-sec windows, such that the mean activity between 6.25 and 5.75-sec prior to movement was used to calculate muscle activity 6-sec before movement, and so on (Cooke et al., 2014).

The acceleration of each putt was determined from the initiation of the downswing phase until the point of contact (Cooke et al., 2014; Cooke et al., 2010; Moore et al., 2012). Average acceleration was calculated for the x, y, and z-axes. Besides impact velocity, Root Mean Square (RMS) jerk and smoothness on the z-axis were computed, as the z-axis is the main axis involved in the putting swing (Cooke et al., 2011; Maxwell et al., 2003).

### Statistical analysis.

The cortical activity manipulation check was subjected to a 3 x 10 repeated measures analysis of variance (ANOVA): Condition (Left, Right, No-hand) x Homologous electrode pairs (T8-T7, P4-P3, P8-P7, F4-F3, F8–F7, C4-C3, FC2-FC1, FC6-FC5, CP2-CP1, CP6-CP5). The T7-Fz connectivity measure during preparation of the golf putt was subjected to a one-way ANOVA of Condition (Left, Right, No-hand). Cardiac and muscle activity were subjected to a 3 x 13 repeated measures ANOVA: Condition (Left, Right, No-hand) x Time Bin (-6, -5, -4, -3, -2, -1, 0, +1, +2, +3, +4, +5, +6). Golf putting kinematics and golf putting performance were both subjected to a one-way ANOVA of Condition (Left, Right, No-hand).

Sphericity was checked and corrected using the Huynh-Feldt correction when necessary. Separate ANOVAs with Bonferroni corrections or polynomial trend analysis were performed when main effects or interactions were found. Effect sizes are reported as partial η squared ($\eta_p^2$). The statistical tests were performed using SPSS (IBM, version 25.0) computer software. Significance was set at $p = .05$ for all statistical tests.

MEMORE for SPSS (MEdiation and MOderation analysis for REpeated measure designs, Montoya & Hayes, 2017) was used to test within-subject mediation effects on golf putting performance associated with left-hand and right-hand contractions. Mediators were individually tested and included EEG, EMG, ECG and kinematics (i.e., club head orientation, swing height and impact force). The mediation effect (B), standard error (BootSE) and 95% CI (low and high) were reported (Montoya & Hayes, 2017).

# Results

## Manipulation check

The results revealed a main effect of Condition, $F(2,42) = 3.95$, $p = .027$, $\eta_p^2 = .16$, with post-hoc analysis revealing a significantly lower asymmetry score for left-hand contractions compared with right-hand contractions ($p = .015$, see Fig. 1). No significant effects were revealed for left-hand contractions compared with no-hand contractions ($p$ = .180) or right-hand contractions compared with no-hand contractions ($p$ = 1.00). No main effect was found for Homologous electrode pairs, $F(3.20,67.15) = 0.93$, $p = .438$, $\eta_p^2 = .04$.

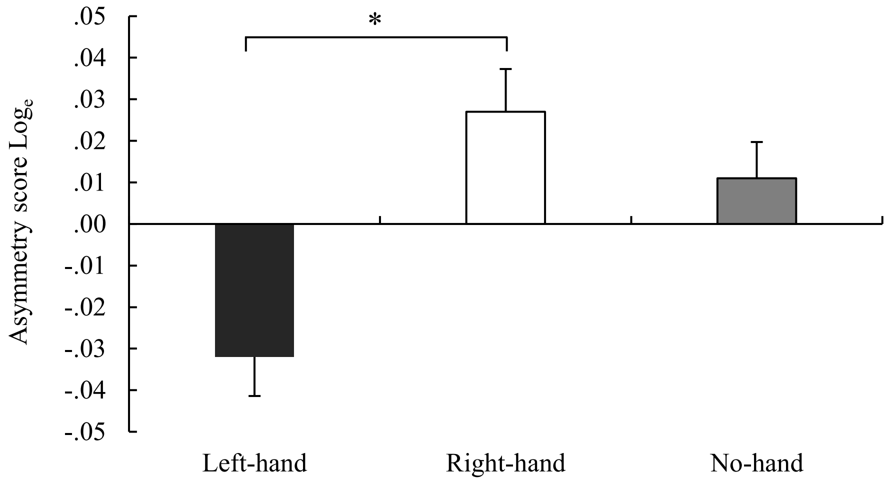


**Fig. 1.** Alpha power asymmetry score per condition. Asymmetry score was calculated by: right hemisphere – left hemisphere (positive values represent higher right-hemisphere power and negative values represent higher left-hemisphere power). Error bars represent standard error of the mean. (* $p < .05$).

## Cortical activity preceding golf putts

The results revealed a main effect of Condition, $F(2,48) = 122.5$, $p < .001$, $\eta_p^2 = .84$. Post-hoc tests revealed that left-hand contractions led to significantly lower T7-Fz connectivity, than right-hand contractions ($p < .001$) or no-hand contractions ($p < .001$, see Fig. 2). Right-hand contractions revealed the opposite effect with significantly higher T7-Fz connectivity compared to left-hand contractions ($p < .001$) and no-hand contractions ($p < .001$, see Fig. 2).

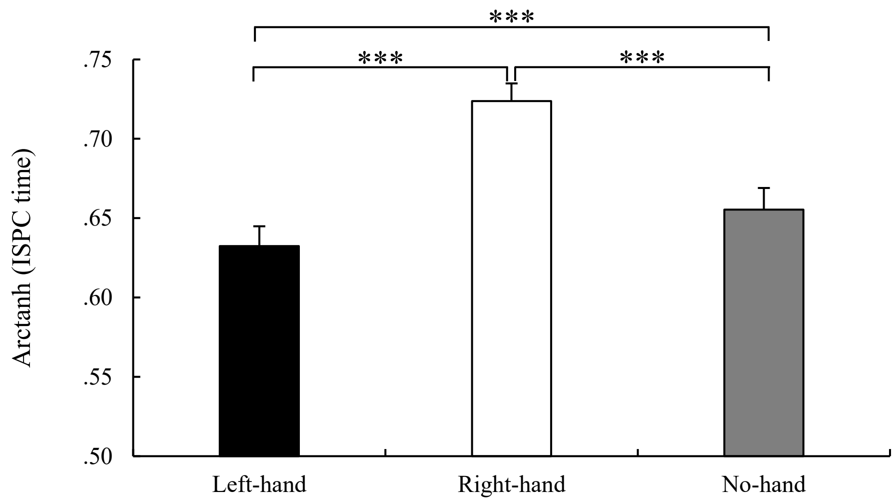


**Fig. 2.** T7-Fz ISPCtime connectivity during each condition and time bin. Error bars represent standard error of the mean. (** p < .001).

## Muscle activity

No Condition x Time Bin interactions were evident for the extensor carpi radialis, F(24,432) = 1.15, $p$ = .290, $\eta_p^2$ = .06, or the flexor carpi ulnaris, F(24,480) = 0.82, $p$ = .715, $\eta_p^2$ = .04. A main effect of Time Bin was evident for the extensor carpi radialis, F(3.73,67.11) = 9.99, $p$ < .001, $\eta_p^2$ = .36, and the flexor carpi ulnaris, F(4.18,83.61) = 13.51, $p$ < .001, $\eta_p^2$ = .40. Post-hoc analysis revealed that for the extensor carpi radialis the variance for Time Bin was best described by a quadratic trend ($p$ < .001, $\eta_p^2$ = .53), with a gradual increase of activity until peak in activity during movement initiation (time zero), which quickly drops back to baseline (see Fig. 3). For the flexor carpi ulnaris, variance for Time Bin was also best described by a quadratic trend ($p$ < .001, $\eta_p^2$ = .68), with similar trends to the extensor carpi radialis (see Fig. 4). Main effects of Condition were not evident for the extensor carpi radialis, F(2,36) = 1.74, $p$ = .191, $\eta_p^2$ = .09, or the flexor carpi ulnaris, F(2,40) = 0.69, $p$ = .510, $\eta_p^2$ = .03.

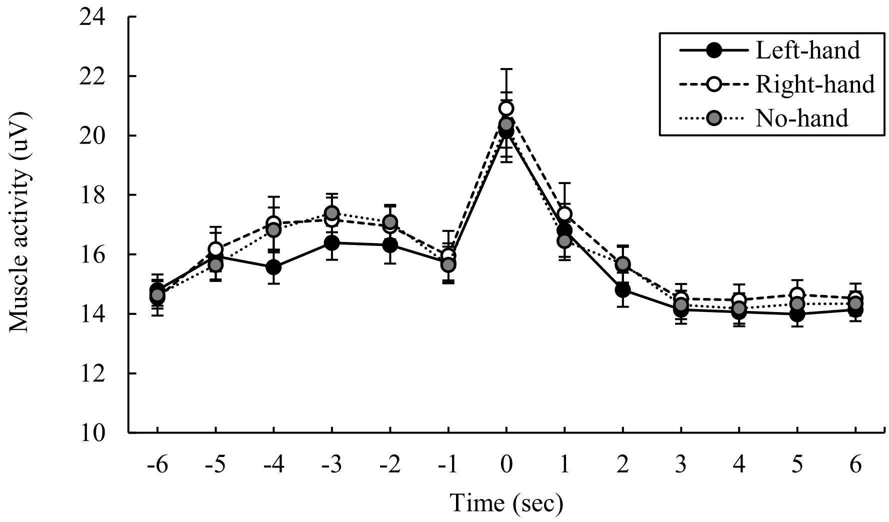


**Fig. 3.** Activity of the extensor carpi radialis in each condition over time. Error bars represent standard error of the mean.

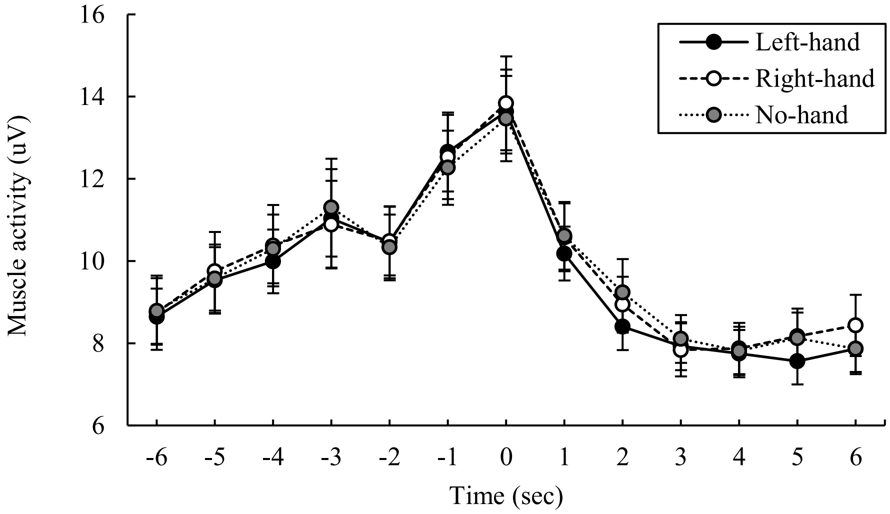


**Fig. 4.** Activity for of the flexor carpi ulnaris in each condition over time. Error bars represent standard error of the mean.

## Cardiac activity

The ECG analysis did not reveal a Condition x Time Bin interaction, F(24,567) = 0.95, $p$ = .532, $\eta_p^2$ = .04, or a main effect of Condition, F(2,48) = 0.62, $p$ = .542, $\eta_p^2$ = .03. A main effect of Time Bin was evident, F(1.57,37.61) = 17.26, $p$ < .001, $\eta_p^2$ = .42. Post-hoc analysis revealed that heart rate differences over time was best described by a cubic trend ($p$ < .001, $\eta_p^2$ = .56). Heart rate decreased during approximately 2-sec preceding movement initiation and then gradually retrurned to baseline in the 6-sec after movement initiation (see Fig. 5).

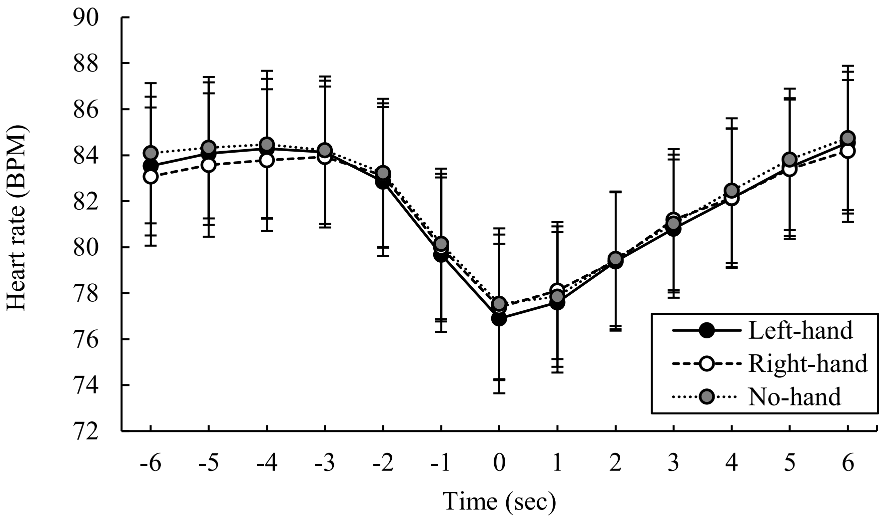


**Fig. 5.** Heart rate in each condition over time (6-sec before until 6-sec after movement initiation). Error bars represent standard error of the mean.

**Golf kinematics**

No differences were evident between conditions for any of the kinematic measures: acceleration on the x-axis, $F(2,48) = 2.60$, $p = .085$, $\eta_p^2 = .10$; acceleration on the y-axis, $F(1.59,38.26) = 0.65$, $p = .493$, $\eta_p^2 = .03$; acceleration on the z-axis, $F(2,44) = 0.55$, $p = .581$, $\eta_p^2 = .02$; impact speed, $F(1.52,36.39) = 0.25$, $p = .718$, $\eta_p^2 = .01$; RMS jerk, $F(2,46) = 0.31$, $p = .738$, $\eta_p^2 = .01$; smoothness, $F(1.59,38.03) = 0.46$, $p = .592$, $\eta_p^2 = .02$.

**Golf putting performance**

No differences were evident between conditions for mean radial error, $F(2,48) = 1.75$, $p = .184$, $\eta_p^2 = .07$.

**Mediation analysis**

Mediation analyses were used to examine whether EEG, EMG, ECG or kinematics mediated the relationship between hand contractions and golf putting performance (mean radial error). Although there was no significant difference in performance between the different hand contraction conditions, there was a significant indirect effect of hand squeezing on performance via T7-Fz connectivity. Within-subject changes in performance following left-hand versus right-hand contractions were mediated by the changes in EEG T7-Fz connectivity induced by these protocols, B = -12.41, BootSE= 4.12, 95% CI [-21.07, -4.94]. The other mediators did not reveal significant indirect effects on performance.

## Discussion

The present study was conducted to examine whether pre-performance unilateral hand contraction protocols influence verbal-analytical engagement in motor performance. A repeated measures crossover design was adopted, measuring psychophysiological markers (neural, cardiovascular and muscular) and performance (distance from the target and movement kinematics) of a golf putting task that was completed immediately after performing a hand contraction protocol (left, right and no-hand). During the hand contraction protocols, measures of alpha power spectra between homologous electrode pairs were computed as a manipulation check to determine whether hand contractions caused different hemispheric activation.

The manipulation check revealed a significant difference in hemispheric asymmetry between left-hand and right-hand contraction protocols, with the left-hand contraction protocol resulting in more right-hemisphere activity and the right-hand contraction protocol resulting in higher left-hemisphere activity (see Fig. 1). These findings are consistent with previous studies (Gable et al., 2013; Harmon-Jones, 2006; Peterson et al., 2008).

Our study is the first to include a no-hand contractions, which makes it possible to compare the effect of left-hand and right-hand contractions relative to no contractions. Asymmetry during the no-hand contraction protocol was not significantly different from either contraction condition, which suggests that hand contractions did not create different asymmetry compared to no-hand contractions. However, hand contractions did achieve different asymmetry compared to each other. The slight rightward bias evident during the no-hand condition is in line with previous studies revealing that right-handedness is related to a bias to rightward hemisphere asymmetry (greater left-hemisphere activity) for resting state alpha power (e.g., Ocklenburg et al., 2019).

As hypothesized, a lower level of T7-Fz connectivity during preparation for putts was revealed after left-hand contractions, compared to right-hand and no-hand contractions. The opposite effect was found for right-hand contractions, revealing higher T7-Fz connectivity compared to left-hand and no-hand contractions. Previous studies have suggested that lower T7-Fz connectivity reflects less verbal-analytical engagement in movements (e.g., Deeny et al., 2003; Gallicchio et al., 2016; Zhu et al., 2011). Left-hand contractions in the present study may therefore have lowered T7-Fz connectivity and reduced verbal-analytical engagement in the putting task, compared to right-hand and no-hand contractions.

Although there was no significant effect of hand contractions on golf putting performance,[3] mediation analysis suggested that hand contractions influenced T7-Fz connectivity, which in turn influenced performance. Beckmann et al. (2013) and Gröpel and Beckmann (2017) speculated that top-down verbal-analytical control processes are the mechanism by which hand contractions influence performance under pressure. Many explanations of skill failure, such as the theory of reinvestment (Masters, 1992; see Masters & Maxwell, 2008 for a review), suggest that attempts to consciously control movements (characterised by verbal-analytical processing), can disrupt normally efficient motor behaviours. Given the hypothesised link between T7-Fz connectivity and conscious verbal engagement of movement, our mediation findings provide some support for their speculation.

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[3] It is acceptable to conduct mediation analysis when there is no significant effect of the independent variable (hand contractions) on the dependent variable (golf putting performance) (see e.g., Kenny, Kashy, & Bolger, 1998).

Although the hand contraction protocols clearly influenced neurophysiological activity, their effects did not extend to the cardiac, muscular or kinematic measures. There were no condition effects for these variables and there were no mediational effects to implicate any of these variables in the relationship between hand contractions and performance. From a theoretical perspective it makes sense that neural measures should be more sensitive to the effects of hand contraction protocols than peripheral measures such as heart rate, because verbal-analytic processes originate from the brain, and any effects they might have on the heart and muscles would always be secondary. Any effects of psychological processes on cardiac and muscular activity could also have been masked by any physical strain on these variables caused by the golf putting task (e.g., standing posture, swinging arms, etc.).

Despite the indirect effect of hand contractions on performance through T7-Fz connectivity, there were no significant performance differences between the different hand contraction protocols. Our participants only performed 130 trials prior to the first hand contraction condition, so they remained relatively inexperienced novices with high inter and intra person performance variability that may have camouflaged any subtle (direct) hand contraction effects. A more cognitively challenging task may reveal performance differences. Zhu et al (2015) also manipulated T7-Fz coherence, using real versus sham tDCS, and also failed to find an effect on golf putting performance alone. However, Zhu et al. (2015) did report a differential effect on golf putting performance under dual-task load (e.g., backwards counting). Alternatively, replicating the experiment with more experienced performers could also increase the likelihood of performance differences. For example, the theory of reinvestment (Masters & Maxwell, 2008) argues that verbal-analytic engagement (e.g., right-hand contractions) would be more detrimental to the performance of autonomous experts than cognitive novices. Effects of condition on the cardiac, muscular and kinematic measures would also be more likely with experienced performers for the same reasons.

A limitation of this study is that we did not control force of grip used by participants during the hand contraction protocol. Consequently, differences in hemisphere asymmetry might have been a function of effort or strength. For example, Hirao and Masaki (2018) showed that force and duration of left-hand contractions had differential effects on hemisphere activity. Additionally, a requirement to achieve a specific force during contractions may require more cognitive resources (e.g., Derosière et al., 2014; Hirao & Masaki, 2018). One solution might simply be to measure grip force and include it as a covariate in analysis of hemisphere asymmetry. This issue should be addressed in further studies.

Another limitation is that we were unable to determine the longevity of the hand contractions with respect to their effect on cortical activity. Studies suggest that the effects of hand contraction protocols last at least 15-min (e.g., Baumer, Munchau, Weiller, & Liepert, 2002). Participants in our study completed 25 trials over approximately a 6-min duration, so it is likely that the effects remained. However, there is little doubt that further research is needed to gain greater understanding of the timecourse of hand contraction effects.

To our knowledge this is the first study reporting neural evidence that left-hand contractions lower verbal-analytical engagement in motor planning of a golf putting task. The additional markers (ECG, EMG, kinematics and performance) did not, however, provide supporting evidence of this effect. These secondary markers may have been insufficiently sensitive to reveal the brain's influence over the body. Nevertheless, it appears that the body (the hands) influenced the brain!

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